Slot waveguide microring modulator on InP membrane

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S. Andreou, [1] A.J. Millan Mejia, [1] M.K. Smit, [1] and J.J.G.M. Van der Tol [1]

[1] Photonic Integration Group (PhI), Dept. of Electrical Engineering, Technische Universiteit Eindhoven, Den Dolech 2, 5612 AZ Eindhoven, The Netherlands

We investigate through simulations a slot waveguide based microring modulator in an InP Membrane On Silicon (IMOS). The slot of the waveguide is filled with an electro-optic polymer. By applying a voltage across the slot, the highly confined electric field across the slot shifts the resonance due to the refractive index change. We show that modulator's speed is limited due to the cavity photon lifetime rather than the RC constant. Low swing voltages (<1 Vpp) and low power consumption (<4 fJ/bit) in combination with reasonable quality factors for high bandwidth (>28 GHz) are possible.

Introduction

Electronic integrated circuits have become a successful technology the last few decades. Their unprecedented high integration density, capability for complex signal processing, high data rate transmission and low cost have allowed them to penetrate in every aspect of our lives. However, it seems that further performance improvements are becoming more difficult, as they are threatened by high power consumption and inability for further miniaturization. Especially the interconnection between components has become a bottleneck. Photonics are a good candidate for overcoming this problem by realizing interconnects in the optical domain.

Different materials have been used, e.g. silicon, crystalline silicon, indium phosphide (InP) and silicon nitride (SiN). InP is the only material that is capable to accommodate optically active functions like light generation and amplification, thus offering a unique property. InP Membrane On Silicon (IMOS) [1] is a photonic technology that utilizes an InP membrane on top of the electronics, thus making it a promising candidate for the realization of optical interconnects. The functionality of such a platform demands a complete set of building blocks that allows the user to build complex circuits. For data transmission, a fundamental building block is the modulator. Different types of modulators have been proposed and fabricated, such as Mach Zehnder Modulators (MZM), electro-absorption (EAM) and micro-ring modulators, all in various versions.

In this study, we will deal with the latter type. The micro-ring modulators offer the smallest footprint due to their resonant nature and the high confinement is provided due to the high index contrast of InP with air. This makes them attractive for applications where high integration density is desired. Furthermore, micro-ring modulators can exhibit low swing voltage and low power consumption. On the other hand, they are inherently optically narrowband and less robust to fabrication tolerances as compared to MZM for example. We investigate through simulations a slot waveguide based micro-ring modulator and present its potential for high modulation speed and low power consumption.

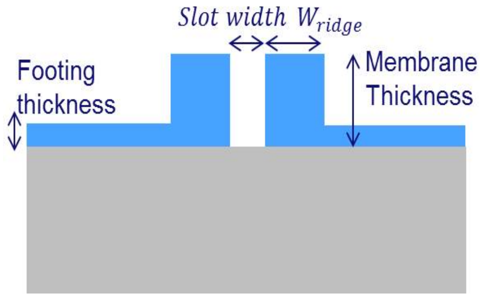

Figure 1: Slot waveguide cross section

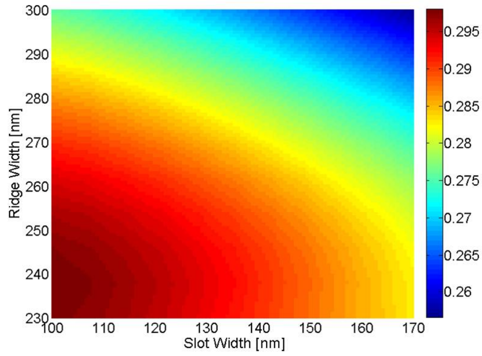

Figure 2: Slot waveguide confinement factor Γ

Slot waveguide based ring

Unlike conventional optical waveguides that guide light in the high index region, slot waveguides [2] (Fig. 1) strongly guide the TE polarized light in the low index region (the slot). The strong confinement of the field in the slot is dictated by the electromagnetic boundary conditions. For TE polarization state the electric field, which is perpendicular to the side-walls, experiences a large discontinuity because the dielectric displacement must be continuous. The confinement factor Γ as a function of the slot width and the ridge width of the slot waveguide is shown in Fig. 2 (calculated with Lumerical Modesolver commercial software). It varies from around 25 to 30 % and is maximized for 100 nm slot width and 240 nm ridge width, in the technologically accessible parameter space.
The slot can be filled with materials like electro-optic polymers (EOP) or liquid crystals. By applying a voltage across the slot a highly localized electric field changes the refractive index of this material and so the effective index of the propagating mode.The top view of the slot waveguide based ring modulator is shown in Fig. 3. The slot is filled with an EOP and the ring is coupled to a normal waveguide. Metal contacts are placed at each side of the ring, inside and outside. The effective index change is calculated with

$$\Delta n_{eff} = \frac{1}{2} n_0^3 r_{33} \frac{V}{d} \Gamma \qquad (1)$$

where n_0 is the refractive index of the electro-optic polymer, r_{33} is the electro-optic coefficient of the polymer, V is the applied voltage and d is the slot width. For the maximum Δn_{eff} a high electro-optic coefficient, a narrow slot and a high Γ are required. The applied voltage V should be minimized in order to ensure low power consumption. The Δn_{eff} is finally related to the shift of the ring resonance that will be discussed later.
The waveguide transmission spectrum exhibits dips at the wavelengths which fulfil the ring resonance condition. By varying the refractive index of the slot the resonance condition changes, thus obtaining a shifted resonance. This can be used to obtain the ON and OFF states of an amplitude modulator. A sufficient extinction ratio ($ER[dB] = P_{ON}[dBm] - P_{OFF}[dBm]$) and a high modulation bandwidth are required for such modulators. For the steady state of a ring modulator the high ER is ensured by the (nearly) critical coupling of the ring, which means that the self-coupling coefficient is equal to the round trip transmission coefficient of the ring. The modulation bandwidth can be re-

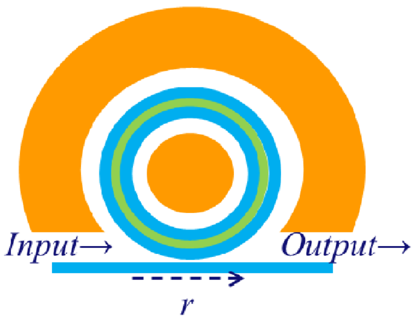

Figure 3: Slot waveguide based modulator - Top view

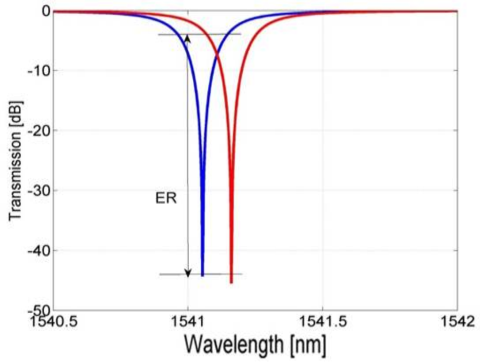

Figure 4: Ring steady state response. The blue curve indicates the initial response and the red curve the shifted one.

stricted by two different mechanisms. The first one is determined by the photon lifetime in the cavity which is directly related to the quality factor Q of the ring. It represents the decay rate of the circulating field. The modulation bandwidth in this case is calculated with

$$f_{ph} = \frac{\omega_0}{2\pi Q} \tag{2}$$

where ω_0 is the optical frequency. A high Q factor results in a long photon lifetime and a slow response while a low Q factor leads to a short lifetime and a higher modulation bandwidth. The second mechanism originates from the electrical domain; this is the RC constant of the modulator. This will be investigated through an electric equivalent circuit of the modulator. The strictest of these two metrics is the ultimate modulation bandwidth limitation.

Results and discussion

The waveguide height equals the membrane thickness of 300 nm and the footing is 50 nm thick. The slot waveguide cross section is chosen for maximum confinement Γ: slot width 100 nm and ridge width 240 nm. The intended EOP has a refractive index of 1.71 and an electro-optic coefficient of 90 pm/V. For these values, voltages below 1 V, the Δn_{eff} can be maximally $5 \cdot 10^{-4}$, which corresponds to a wavelength shift of 0.2 nm.

With a full 3D FDTD simulation we obtain that for a 7.5 μm radius ring the round-trip transmission coefficient is 0.99 and for a 500 nm gap between the bus and the ring, we approach the critical coupling condition. This can be seen in Fig. 4 where the blue curve almost goes to zero at the central wavelength. The shifted resonance is indicated in the same figure with the red curve for a voltage of 0.8 V. The two curves show a high ER at the steady state regime and a small power penalty (3 dB) along with a small swing voltage.

For this ring resonator the Q factor is 6800 which yields a photon lifetime limited bandwidth a little over 28 GHz. In Fig. 5 the cross section of the modulator and the electric equivalent circuit are shown. C_p indicates the parasitic capacitances between the metal pads, which are calculated with Comsol, C_s is the slot capacitance and R_o and R_i are the

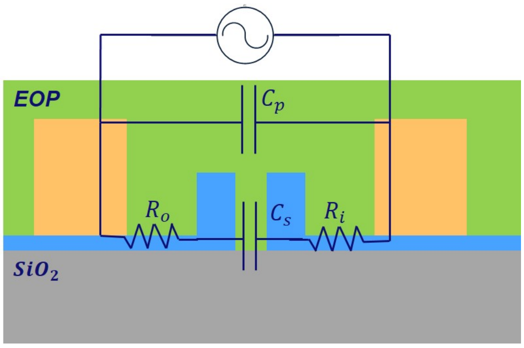

Figure 5: Modulator electric equivalent including resistances and capacitances.

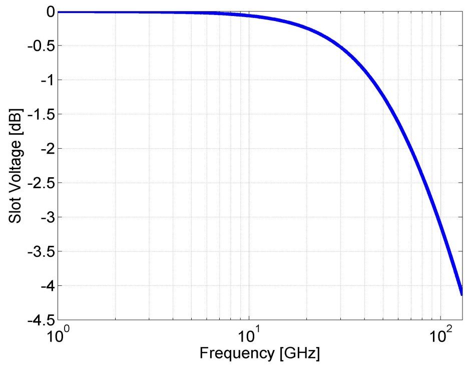

Figure 6: Response of electric equivalent. The 3 dB bandwidth is much higher that the photon lifetime limited bandwidth.

resistances of the InP layer outside and inside the ring respectively. The capacitances are in the order of 5-6 fF. The resistances can be calculated from the sheet resistance of InP and depend on the footing thickness (30 nm), the slot-pad distance ($\sim$4 μm) and the doping level (n-type, $10^{18} \cdot cm^{-3}$) of the InP. The frequency response is shown in Fig. 6. The 3 dB bandwidth is slightly below 100 GHz. This finding indicates that such a modulator is not limited by its RC constant but rather by its quality factor. In other words, by decreasing the Q factor the modulation bandwidth can be further increased. This can be done by using a ring with smaller radius and subsequently higher losses. A direct consequence of this would be the necessity for a higher swing voltage due to the wider resonances in order to restore the ER and the penalty. Finally, the power consumption can be calculated from the equivalent circuit. The energy per bit is essentially the one needed to charge all the capacitances and is proportional to CV^2. The energy consumption is calculated to be 3.8 fJ/bit, which is very low and comparable to the state of the art ring modulators [3, 4].

Conclusions

We propose a slot waveguide based ring modulator which shows good potential for achieving high bandwidth and low power consumption. The specific modulator shows that a bandwidth over 28 GHz is possible which is limited by the photon lifetime rather than the RC constant of the modulator. The energy consumption is calculated to be lower than 4 fF/bit.

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